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UTILIZATION OF POWDERED METAL AND SHOT PEENING RESIDUAL STRESS TO MAXIMIZE COST AND PERFORMANCE BENEFIT OF HIGHLY LOADED GEARING

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ABSTRACT
The primary benefit of powdered metal (PM) gearing is reduced cost of manufacturing making it an obvious choice for lower load applications. The perception that PM gears are only limited to low load classes has been changing with recent developments in higher density PM technology and advanced manufacturing techniques such as powder forging, isostatic pressing, conventional compaction, surface densification, and activated sintering.

This paper will focus on bending fatigue strength improvements of PM gearing from recent improvements in PM technology combined with the established technology of shot peening. Factoring in the significant cost savings of PM manufacturing, PM gears with shot peening have the potential to replace higher load applications currently served by wrought gearing. This paper addresses gear applications limited by bending fatigue and not other failure modes.

KEY WORDS
High Density, Powder Metal, Bending Fatigue, Shot Peening, Residual Compressive Stress

INTRODUCTION
Increasing the load carrying capacity of gearing has been of principle importance since gears have been in existence. In modern day manufacturing, the cost of gear production continues to play a significant role in selection and implementation of gear design, materials, heat treatment and subsequent finishing operations.

Generally speaking, conventional press and sinter PM technology by itself has not achieved the bending performance properties of wrought steel gears. With advanced processing techniques and the addition of shot peening, the performance gap has been significantly reduced to eliminated. Even with the value added process of shot peening, PM components can have strong cost advantages over wrought steel gearing.

PM TECHNOLOGY
Usage of lower cost, higher performance manufacturing technology is heavily driven by, but not limited to, the automotive industry. Long service life, high quality requirements and continued reduction in cost are essential in manufacturing and design. The primary benefit of the PM process is the ability to eliminate traditional manufacturing steps of machined gears to achieve near-net shapes. This net shape capability translates to significant cost savings.

Emerging PM technology to increase load bearing capacity is primarily focused on improvements in density. Additional variations of chemistry and heat treatment are not believed to be the main limiting factors in advancing PM gear applications.

A secondary benefit of PM technology is very uniform and isotropic material properties. When comparing PM steels to their wrought steel counterparts, the tendency for alloy segregation may be significantly reduced. Each particle in the powder metal mix is considered a microingot. This uniformity together with the resulting isotropy from PM processing results in very consistent response to heat treating and subsequent machining, grinding and finishing operations.

The PM industry is currently advancing technologies for producing components with near-fully dense properties. Near fully dense is defined as less than 1% residual porosity. Two of these technologies that will be discussed are Power Forging and Isostatic Pressing.

Powder Forging – This technique is used in mass produced PM steel parts that essentially have wrought steel properties. High volume components such as automotive transmission and engine parts are currently being made with this process. Densities of 7.82-7.84 g/cm^3 are currently possible with powder forging.

Powder forging manufacturing begins with a "green compact". This consists of a preform that has been pressed into shape at room temperature. The preform is then heated to forging temperature and restruck in a forging tool until final density is reached.

Isostatic Pressing – Isostatic pressing differs from other methods of compaction in that this process is accomplished in a pressurized fluid such as oil, water or gas. The powder is encapsulated in a flexible, sealed container (or can) that allows forming into near-net shapes of varying size and part complexity.

Hot isostatic pressing is performed in an inert gas atmosphere, most commonly nitrogen, argon or helium, that is contained in a pressure vessel. Both the powder (to be pressed into a formed part) and atmosphere are heated to temperatures as high as 2,300˚F (1260˚C). Common pressure levels are 15,000 psi (104 MPa). Typical densities for hot isostatic pressing are 7.2 – 7.4 g/cm^3. Some companies reportly are able to achieve 7.5 – 7.8 g/cm^3 with their proprietary processes.

The powder to be processed is vacuum sealed within a container that will deform plastically at elevated temperature and pressure. The pressing and sintering operation occur simultaneously in the heated pressure vessel. The container is then separated from the near-net component through methods such as leaching or machining.

Alternatively, a previously formed component of greater than 92% of theoretical density may be pressed to full density without the use of the costly encapsulation stage.

Emerging PM Technologies – Because of some economic and dimensional precision issues with powder forging and hot isostatic pressing, the focus on recent PM technological advances is on enhancements to conventional compacting, surface densification, and activated sintering technologies as means for achieving gearing related mechanical properties that are equivalent to wrought steels [1,2].

SHOT PEEN ENHANCEMENT

Shot peening is an established technology used for inducing residual compressive stress at the surface of metal components. The residual stress is a function of the hardness/strength properties of the gear surface such that heat treatment plays a significant role in the resultant residual compressive stress profile.

For applications subject to mechanical fatigue loading, residual stresses are additive with applied stresses. The applied bending stress of a gear root is reduced by the amount of residual compression induced from the shot peen process. Shot peening modifies the residual stress distribution at the outer surface which is usually the initiation site of a typical fatigue failure. The typical location of a bending failure for a gear is the transition/tangent point between the gear root and gear flank.

For gearing applications, the process is most commonly accomplished with steel shot media in the size range of 0.007" to 0.046" ø (0.18 to 1.17 mm ø). The shot media should be fully hardened to 55-62 HRC for maximum compressive magnitude and depth properties. Reduced hardness media (45-52 HRC) is available when tooth flank surface finish is a concern. A typical residual stress distribution of a carburized & fully hardened, shot peened (with fully hardened shot), wrought gear steel is shown in Fig. 1.

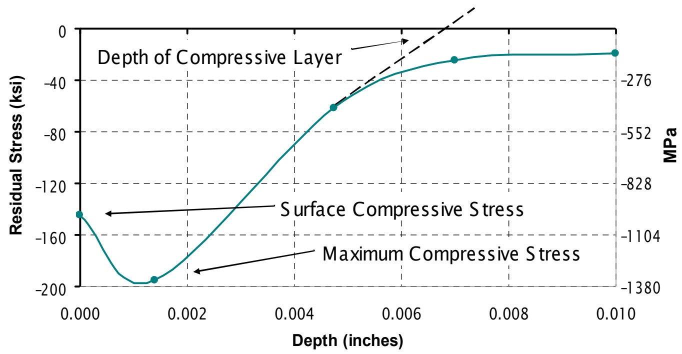

Figure 1 – Typical Residual Stress Distribution From Shot Peened Wrought Steel

It should be noted that the curve does not cross the neutral axis such that the surface residual compressive stresses are balanced with sub-surface residual tensile stresses for static rebalancing. The reason is that the carburized layer (which is significantly deeper than the shot peen layer) has residual compression prior to the shot peening. The static rebalancing would occur much deeper than what is shown in Fig. 1. A dashed line is shown to represent the depth of the shot peen layer by extending the curve from its positively sloping portion.

It is generally accepted for most gearing applications that bending fatigue strength improves with increasing residual compression. Figure 2 demonstrates the trend of improved bending fatigue with increasing residual compressive stress. Figure 2 is a compilation of results using carburized 20MnCr5 in single tooth pulsator tests. The gears were 8.0 mm module with 20 teeth [3].

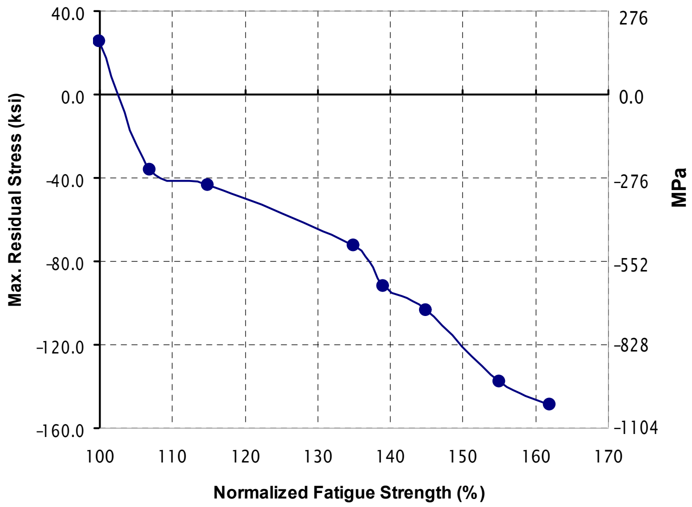

Figure 2 – Increased Fatigue Strength Correlated to Increased Maximum Compressive Stress

All results in Fig. 2 are normalized to 100% on the horizontal axis. The graph shows that the highest magnitude of residual compression (~ 150 ksi, 1035 MPa) showed an increase in fatigue strength of approximately 60% when compared to the baseline (100%) that had approximately 25 ksi (173 MPa) of residual tension.

As stated previously, the residual stress induced from the shot peening is heavily influenced by the properties of the material being peened. This applies to both wrought steel and PM gears. Applying this principle to PM components, this means that shot peening will produce more compressive stress on higher hardness and higher density PM components resulting in optimum load carrying properties. Lower density PM components will still respond with compressive stress, however, they lack the strength to retain higher magnitudes of compressive stress.

<u>DISCUSSION OF TEST DATA</u>

This section will present available test data on shot peening of powder metal gears. Several different types of data are presented including tooth root bending fatigue data. This fatigue data was acquired using single tooth pulsator (STP) tests.

It should be noted that fatigue strength data from STP tests should be adjusted downward as the specific tooth (teeth) that were tested are not necessarily the weakest on the gear. In power recirculation tests which are more applicable to real life conditions (and more expensive to perform), the weakest tooth always fails. Test results indicate a downward adjustment to ~ 80% of the STP testing improvement would be realistic [4].

The principles of fatigue failure should also be mentioned. A typical S-N curve plots the applied stress versus number of cycles. The higher the number of cycles prior to shot peening the greater the enhancement with the addition of shot peening. This is because shot peening lowers the net stress experienced at the surface of the gear. A reduced net stress theoretically brings the resultant stress closer to the endurance limit. Figure 3 (that does not apply to any specific material or application) demonstrates this concept.

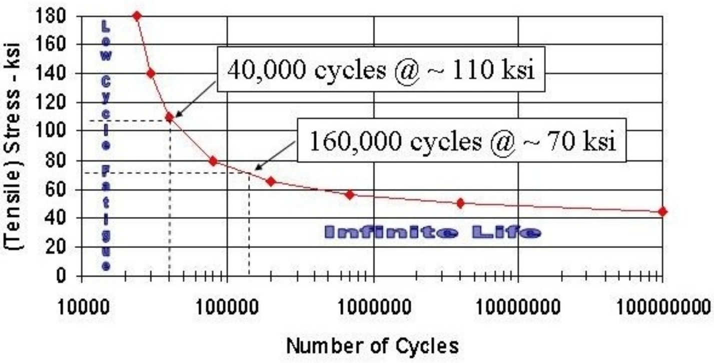

Figure 3 – Typical Stress vs Load Cycles (S-N) Curve

Using this principle, one could assume that if fatigue strength results were analyzed (before and after shot peening) at 500,000 cycles compared to 2 million cycles the percent improvement would not be as significant. If fatigue strength were analyzed at 4 million cycles (compared to 2 million cycles), theoretically the fatigue strength improvement should be greater.

Case Study #1 - The German Federal Ministry of Education and Research tested powdered metal alloys and their suitability for gearing applications. MSP4.0Mo based powdered metal gear alloys were tested against 20MnCr5 case hardened, wrought steel gears. Tooth root load carrying capacity tests were performed using single tooth pulsator tests at 2 million cycles. All gears were 3.5 mm module. The results are shown in tabular format [5].

	Wrought Reference Gear	Variation 1 (7.72 g/cm^3) MSP4.0Mo	Variation 2 (7.76 g/cm^3) MSP4.0Mo-0.1Nb
Non-Peened Fatigue Strgth	131 ksi 900 MPa	100 ksi 685 MPa	108 ksi 745 MPa
Shot-Peened Fatigue Strgth	N/A	145 ksi 1,000 MPa	145 ksi 1,000 MPa

Note: All results are shown at 50% failure probability

The above test study shows a decrease of ~ 20% (25% & 18% respectively) when comparing the non-peened powdered metal variations to the (non-peened) wrought reference gear. With the addition of shot peening both examples exceeded the (wrought) reference gear by ~ 9%.

Assuming an average 104 ksi (100 & 108 ksi) fatigue strength prior to shot peening of the non-peened powder metal variations and 145 ksi with the addition of shot peening, the fatigue strength improvement is ~ 39%. With the previously mentioned STP to power recirculation adjustment, the shot peened value can be adjusted to ~ 136 ksi (a 31% improvement) for calculated service requirements.

Case Study #2 - Another test study was performed on PM test bars with a machined radius acting as a stress concentration (stress factor, K=1.49). The material was Fe-2%, Cu-2.5%, Ni- with a density of 7.6 g/cm^3. Tests were performed under both uniform and variable loading. In addition to varying test loads, the test matrix examined various sintering treatments. Figure 4 depicts the results. Below the figure is an explanation of the curves labeled in the legend of the graph [6].

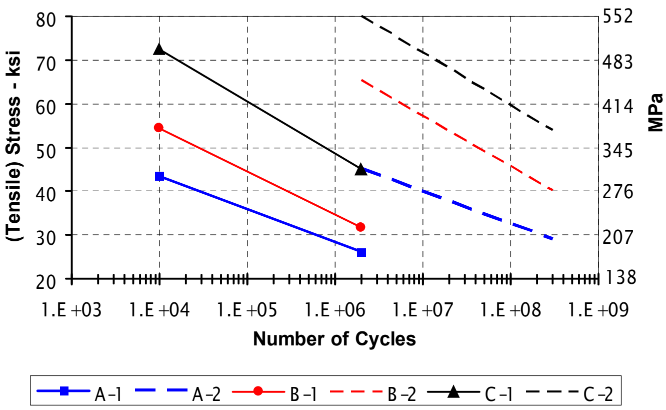

Figure 4 – Fatigue Life Curves of Fe-2%, Cu-2.5%, Ni- With a Density of 7.6 g/cm^3

- A-1: As Sintered, Constant Loading
- A-2: As Sintered, Variable Loading
- B-1: Sintered & Shot Peened, Constant Loading
- B-2: Sintered & Shot Peened, Variable Loading
- C-1: Sintered, Carbonitrided & Shot Peened, Constant Loading
- C-2: Sintered & Shot Peened, Variable Loading

Note: All shot peening performed to a 0.016" A intensity.

This data supports the theory that harder, higher strength materials achieve better fatigue performance as they are able to retain higher magnitudes of residual compressive stress. When comparing the constant loading conditions at 1 million cycles, the as sintered (A1) condition has a fatigue strength of ~ 28 ksi (193 MPa). When carbonitrided and shot peened (C1) the fatigue strength increases to ~ 48 ksi (331), a 71% improvement.

Case Study #3 – Fe-Mo PM alloy gears at a density of 7.5 g/cm^3 were tested at an endurance limit of 3 million cycles. The gears were hardened to 60 HRC and shot peened (0.016" A intensity) with fully hardened 62 HRC shot. The following results are from single tooth loading [7].

- Sintered & Case Hardened (baseline): 130 ksi (900 MPa)
- Sintered, Case Hardened & Ground: 112 ksi (770 MPa)
- Sintered, Case Hardened & S/P: 149 ksi (1030 MPa)

Shot peening improved the baseline condition by 19 ksi (~ 15%). It is worth noting that that the endurance limit of the gear tooth roots that were ground decreased 18 ksi (~ 14%) from the baseline condition. It is generally believed that a smoother surface will respond better under fatigue conditions as potential crack initiation sites are assumed to be eliminated. What is sometimes neglected is the fact that grinding under certain circumstances can introduce residual tensile stresses if not properly controlled. Residual tensile stresses will act to accelerate a fatigue failure as they are additive with applied tensile stresses. It is believed this is what contributed to the decrease in fatigue life however this was not the focus of this study.

Case Study #4 – Residual stress comparisons were made between shot peening a hardened surface with different shot grades of shot hardness. A carbonitrided, powder metal Fe-1.5% alloy (density = 7.4 g/cm^3) surface was shot peened with fully hardened and regular hardness shot media. Figure 5 shows the residual stress comparison [6].

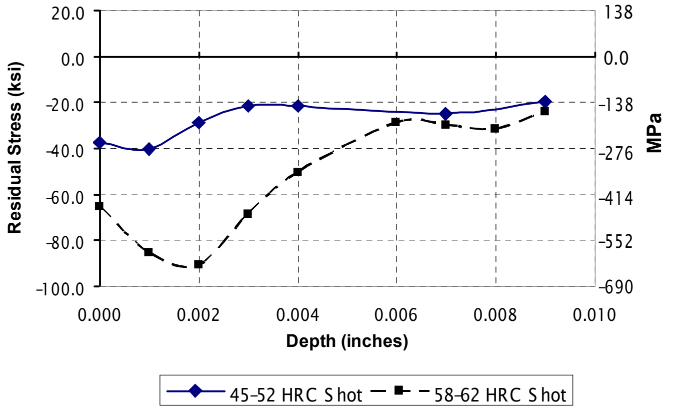

Figure 5 – Residual Stress Plot of Shot Peened Carbonitrided PM With Different Grades of Shot Hardness

It should be noted that both curves do not cross the neutral axis due to residual compression created from the carbonitriding process prior to shot peening. Figure 5 shows significantly more residual compression when using a harder shot media. Though bending fatigue tests for comparing the two were not available, the residual stress from the higher shot hardness would most likely produce better results in bending fatigue.

Case Study #5 – Tooth root bending fatigue studies were performed using pulsator tests to compare a reference wrought gear steel to a 7.5 g/cm^3 powdered metal gear. Both gears were 3.5 mm module consisting of 25 teeth and case hardened to 60 HRC. The wrought gear was a 16MnCr5 steel and the powdered metal gear was Fe-3.5Mo alloy content.

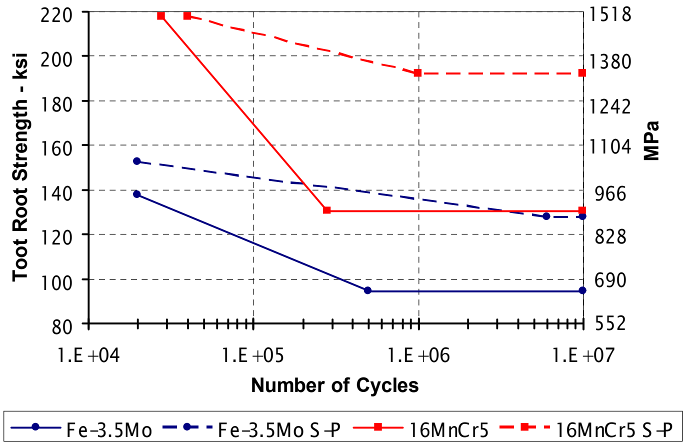

Figure 6 – Fatigue Life Curves Comparing a Reference (16MnCr5) Wrought Steel to a 7.5 g/cm^3 Powdered Metal (Fe-3.5Mo) With and Without Shot Peening

In Figure 6 the powdered metal gear results are depicted with the blue curves. The endurance limit improved ~ 35% with the addition of shot peening. The endurance limit improved from ~ 95 ksi (650 MPa) to ~ 128 ksi (880 MPa). The endurance limit of the shot peened powdered metal compares very closely with the non-peened 16MnCr5 material. Shot peening was performed at 0.013" A (0.32 mm A) intensity for all samples.

In Figure 6 the reference 16MnCr5 steel gear results are depicted with the red curves. The endurance limit improved ~ 45% with the addition of shot peening. The unpeened condition was ~ 131 ksi before shot peening and ~ 190 ksi after shot peening. Since the unpeened material has a higher strength than the unpeened powder metal gear, the 16MnCr5 is able to retain more residual compression from shot peening resulting in more overall improvement in fatigue strength from shot peening. Using the previously mentioned STP to power recirculation adjustment, the endurance strength improvements can be adjusted to ~ 29% (from ~ 35%) for the powdered metal gears and to ~ 36% (from ~ 45%) for the wrought steel gear [8].

Case Study #6 – Bending fatigue tests on powder forged C-0.5%, Cu-2% components with a density of 7.82 g/cm^3 improved fatigue strength by 27% over the non-peened components (at 90% reliability levels) [9]. It should be noted that the components in this test were automotive connecting rods and not gears. The reason they were included as part of this paper was that the usage of high density PM and the failure mode was bending fatigue which is typical of all other case studies presented in this paper.

CONCLUSION

The growth of the powder metal market is directly a function of the available applications it can serve with its current cost advantages. The current market for gearing covers a broad spectrum from non-critical, low load applications to critical, high load applications. The PM gear market is naturally limited by its mechanical performance capability. Recent improvements in the manufacturing technologies of powdered metal have allowed it to be considered for higher strength gear applications. Higher bending strength PM applications are highly predicated on higher densities and subsequent heat treating and metal finishing operations.

Typical high load gear applications are susceptible to bending fatigue failure in the gear tooth root. Shot peening is a recognized process to induce residual compressive stress. It is also highly dependant on PM density and heat treatment. Test data was presented to support the consideration of PM bending fatigue strength improvements through the use of shot peening. PM gearing even with the value added service of shot peening represent significant cost advantages over their wrought steel counterparts.

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